



Contribution of fungi to primary biogenic aerosols in the atmosphere: active discharge of spores, carbohydrates, and inorganic ions by Asco- and Basidiomycota

W. Elbert, P. E. Taylor, M. O. Andreae, U. Pöschl

► To cite this version:

W. Elbert, P. E. Taylor, M. O. Andreae, U. Pöschl. Contribution of fungi to primary biogenic aerosols in the atmosphere: active discharge of spores, carbohydrates, and inorganic ions by Asco- and Basidiomycota. Atmospheric Chemistry and Physics Discussions, 2006, 6 (6), pp.11317-11355. hal-00302269

HAL Id: hal-00302269

<https://hal.science/hal-00302269>

Submitted on 15 Nov 2006

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Contribution of fungi to primary biogenic aerosols in the atmosphere: active discharge of spores, carbohydrates, and inorganic ions by Asco- and Basidiomycota

W. Elbert¹, P. E. Taylor², M. O. Andreae¹, and U. Pöschl¹

¹Max Planck Institute for Chemistry, Biogeochemistry Department, P.O. Box 3060, 55020 Mainz, Germany

²Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA 91125, USA

Received: 20 September 2006 – Accepted: 6 November 2006 – Published: 15 November 2006

Correspondence to: W. Elbert (elbert@mpch-mainz.mpg.de)

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

Abstract

Spores and related chemical compounds from actively spore-discharging Ascomycota (AAM) and actively spore-discharging Basidiomycota (ABM) are primary biogenic components of air particulate matter (characteristic size range 1–10 μm). Measurement results and budget calculations based on investigations in Amazonia (Balbina, Brazil, July 2001) indicate that the forcible discharge of fungal spores may account for a large proportion of coarse air particulate matter in tropical rainforest regions during the wet season. For the particle diameter range of 1–10 μm , the estimated proportions are ~25% during day-time, ~45% at night, and ~35% on average. For the sugar alcohol, mannitol, the budget calculations indicate that it is suitable for use as a molecular tracer for actively discharged basidiospores (ABS), and that the literature-derived emission ratio of about 5 pg per ABS may be taken as a representative average. ABM emissions may account for most of the atmospheric abundance of mannitol, and can explain the observed diurnal cycle (higher abundance at night). ABM emissions of hexose carbohydrates might also account for a significant proportion of glucose and fructose in air particulate matter, but the literature-derived ratios are not consistent with the observed diurnal cycle (lower abundance at night). AAM emissions appear to account for a large proportion of potassium in air particulate matter over tropical rainforest regions during the wet season, and they can also explain the observed diurnal cycle (higher abundance at night). The results of our investigations and budget calculations for tropical rainforest aerosols are consistent with measurements performed at other locations.

Based on the average abundance of mannitol in particulate matter, which is consistent with the above emission ratio and the observed abundance of ABS, we have also calculated a value of $\sim 17 \text{ Tg yr}^{-1}$ as a first estimate for the global average emission rate of ABS over land surfaces. Comparisons with estimated rates of emission and formation of other major types of organic aerosol ($\sim 47 \text{ Tg yr}^{-1}$ of anthropogenic primary organic aerosol; $12\text{--}70 \text{ Tg yr}^{-1}$ of secondary organic aerosol) indicate that emissions from actively spore-discharging fungi should be taken into account as a significant

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

source of organic aerosol. Their effects might be particularly important in tropical regions, where both physicochemical processes in the atmosphere and biological activity at the Earth's surface are particularly intense, and where the abundance of fungal spores and related chemical compounds are typically higher than in extratropical regions.

1 Introduction

Biogenic aerosols are ubiquitous in the Earth's atmosphere and they influence atmospheric chemistry and physics, the biosphere, climate, and public health. They play an important role in the spread of biological organisms and reproductive materials, and they can cause or enhance human, animal, and plant diseases. Moreover, they influence the Earth's energy budget by scattering and absorbing radiation, and they can initiate the formation of clouds and precipitation as cloud condensation and ice nuclei (Dingle, 1966; Schnell and Vali, 1972; Cox and Wathes, 1995; Andreae and Crutzen, 1997; Hamilton and Lenton, 1998; Andreae et al., 2002; Taylor and Jonsson, 2004; Jaenicke, 2005; Lohmann and Feichter, 2005; Pöschl, 2005; Dusek et al., 2006; McFiggans et al., 2006; Sun and Ariya, 2006; and references therein). The composition, abundance, and origin of biogenic aerosol particles and components are, however, still poorly understood and quantified.

Primary biogenic aerosol (PBA) particles and components are emitted directly from the biosphere to the atmosphere. Examples of PBA particles are pollen, bacteria, fungal and fern spores, viruses, and fragments of animals and plants (Simoneit and Mazurek, 1982; Matthias-Maser and Jaenicke, 1992; Artaxo and Hansson, 1995; Bauer et al., 2005). PBA components comprise the non- or semi-volatile chemical substances contained in PBA particles as well as the biogenic substances contained in other types of aerosol particles such as soil dust, sea spray, etc. (Fuzzi et al., 2006a).

The occurrence and dispersion of microorganisms and spores in the air has been discussed and investigated very early in the history of aerosol science (Ehrenberg,

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

1830; Pasteur, 1860a, 1860b). Since then, aircraft, balloon, and rocket measurements have shown that PBA particles are not only ubiquitous over land and oceans but also transported to high altitudes (up to 80 km) and over long distances (Scheppergrell, 1924; Proctor, 1934; Meier, 1935; Rogers and Meier, 1936; Pady et al., 1950; Gregory, 1978; Imshenetsky et al., 1978; Watson and DeSousa, 1983; Griffin et al., 2001; McCarthy, 2001; Brown and Hovmoller, 2002; Yeo and Kim, 2002; Wainwright et al., 2003; Prospero et al., 2005).

Pollen grains, fern spores, large fungal spores, and other large PBA particles typically belong to the coarse fraction of air particulate matter, with aerodynamic diameters up to one hundred micrometers. PBA particles and components are, however, also found in intermediate and fine fractions of air particulate matter, with aerodynamic diameters less than 10 μm (PM10), 2.5 μm (PM2.5), and 1 μm (PM1), respectively: most fungal spores, small fragments and excretions of plants and animals, bacteria, viruses (Górny et al., 2002; Taylor et al., 2004); carbohydrates, proteins, waxes, ions, etc. are in this size range (Fish, 1972; Beauford et al., 1975; Miguel et al., 1999; Zhang and Anastasio, 2003; Franze et al., 2005; Pöschl, 2005). So far, however, the biological, chemical, and physical effects and mechanisms involved in the emission and dispersion of PBA particles and components have received little attention in biogeoscience and atmospheric research.

Here, we present and discuss evidence that the forcible discharge of spores from certain fungi is accompanied by the emission of aqueous droplets containing carbohydrates and inorganic ions. This is likely to account for a large proportion of these compounds in air particulate matter, especially in pristine tropical rainforests. We summarize the information available from earlier scientific publications and present new measurement data and budget calculations for aerosol samples from Amazonia. Furthermore, we derive a first estimate for the global emission rate of actively discharged basidiospores.

**Contribution of fungi
to biogenic aerosols**

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2 Active discharge of fungal spores by Ascomycota and Basidiomycota

The number of different fungal species in the biosphere is assumed to be in the range of 1–1.5 million, but only about 40 000 are well-characterized (Rossman, 1994). They are usually grouped into the three divisions (phyla) of Ascomycota, Basidiomycota, and Zygomycota. A fourth category is called “mitosporic fungi” (formerly known as Chytridomycota, Deuteromycetes or “Fungi Imperfecti”) (Ribes et al., 2000).

Fungi exist in terrestrial and aquatic habitats, and their reproduction proceeds via budding or sporulation, using a variety of dispersal mechanisms (Buller, 1909–1950; Ingold, 1971, 1999). Here we concentrate on those species of Ascomycota and Basidiomycota that actively discharge their spores into the air, which we designate as “actively spore-discharging Ascomycota” (AAM) and “actively spore-discharging Basidiomycota” (ABM).

2.1 Actively spore-discharging Ascomycota (AAM)

AAM exist as saprophytes on dead biomass as well as endophytes or parasites in/on living organisms. In combination with algae, they form lichens which live as epiphytes on plants or on other surfaces, such as rocks, house walls etc. They are found in most regions and climate zones of the world.

The spores of AAM, which we designate as actively discharged ascospores (AAS), are typically 2–20 μm in diameter (Buller, 1909; Ingold, 2001b) and mature within apothecia. These are composed of small sacks (asci) filled with epiplasmic fluids, and they contain a mix of organic and inorganic solutes. For example, a mature ascus of *Giberella zeae* holds a liquid volume of $\sim 7 \times 10^{-15} \text{ m}^3$ with mannitol ($4.7 \pm 2.2 \times 10^{-12} \text{ g}$), potassium ($4.6 \times 10^{-11} \text{ g}$), and chloride ($1.4 \times 10^{-11} \text{ g}$) as the main solutes (Trail et al., 2005). Glycerol and proline (37 ± 6 and $8 \pm 3 \text{ mmol/L}$, respectively) were found in the ascus sap of *Ascobolus immersus* (Fischer et al., 2004). To our knowledge, other data on the chemical composition of ascus sap are not available.

The asci are pressurized osmotically and, upon discharge, spores and droplets of

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

epiplasmic fluid are vigorously ejected through a narrow aperture at the tip of the bursting asci (Buller, 1909; Ingold, 2001a; Trail et al., 2002). The size and number of the ejected aqueous droplets are similar to the size and number of spores (twice as many droplets in the case of *Giberella zeae*, Trail et al., 2002). The discharge distance ranges from about one to several hundred millimeters in still air (Buller, 1909; Ingold, 1971; Meredith, 1973).

Raynal (1990) found that individual apothecia of *Sclerotinia trifoliorum* ejected up to 4.7×10^6 AAS over their entire life cycle. Ingold (1971) reported that individual apothecia of *Cookeina sulcipes* can discharge $3\text{--}24 \times 10^6$ AAS, and Hong and Michailides (1998) determined a release of $2\text{--}37 \times 10^6$ AAS per AAM fruiting body of *Monilinia fruticola*. Venette (1998) reported that a single apothecium of *Sclerotinia sclerotiorum* can discharge $2\text{--}30 \times 10^6$ AAS over a period of several days and estimated a potential spore load of $0.2\text{--}3 \times 10^{12}$ AAS for this fungus per ha of grain field (Table 1).

2.2 Actively spore-discharging Basidiomycota (ABM)

ABM comprise mushrooms, bracket and jelly fungi, smut and rust fungi, as well as basidiomyceteous yeasts (mirror yeasts). The rusts have a complex life cycle with several stages, and during one of these emit actively discharged basidiospores (ABS), which are also called ballistospores. Mirror yeasts are dimorphic fungi; they can grow in a hyphal form like yeasts, but can also discharge ABS. Most of the other ABM emit ABS from basidia (little pedestals) aligned along gills, in tubes, or on the surface of their fruiting bodies.

The diameter of ABS typically range from 2 to $10 \mu\text{m}$. (Ingold, 2001b). Their active discharge was noted in the 19th century, but only recently was the discharge mechanism resolved and termed “surface tension catapult” (Turner and Webster, 1991; Pringle et al., 2005). It involves an aqueous droplet near the basal end of the spore called the “Buller’s drop” (Buller, 1915, 1922; Buller and Vanterpool, 1925), and a thin liquid film on the distal end of the spore. At high relative humidity they both grow by hygroscopic uptake of water vapor. Upon reaching a size comparable to the spore,

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the Buller's drop and the liquid film merge, and the generated momentum propels the spore, enveloped by the liquid, away from the basidium – typically over distances of 0.1–1.5 mm (Webster et al., 1989; Turner and Webster, 1995; Ingold, 1999; Pringle et al., 2005).

The solutes found in Buller's drops of the basidiomycetous yeast *Itersonilia perplexans* are mainly hexoses and mannitol (3.8 and 5.3 pg per spore, respectively) plus smaller (but not quantified) quantities of inorganic ions like phosphate, sodium and potassium (Webster et al., 1995). To our knowledge, other data on the chemical composition of the Buller's drop are not available.

Buller (1909) reported that a single fruiting body of a mushroom (basidiocarp) can discharge as many as $4\text{--}10 \times 10^7$ ABS per hour (*Psalliota campestris* and *Coprinus comatus*), 6.8×10^8 ABS per week (*Daedalea confragosa*), or $1\text{--}10 \times 10^{10}$ ABS per year (*Polyporus squamosus*), respectively (Table 1). Meredith (1973) reported discharge rates of 3×10^{10} ABS per day over periods up to 6 months for artist's conk (*Ganoderma applanatum*).

Besides AAM and ABM, other fungal species also actively discharge their propagating units with liquid jets or droplets, e.g., *Basidiobolus*, *Conidiobolus*, *Entomophthora*, *Pilobolus* and *Sphaerobolus stellatus* (Buller, 1909; Couch, 1939; Page, 1964; Ribes et al., 2000). The chemical composition of these liquids is, however, not known, and thus not included in the present study.

3 Abundance of fungal spores and related chemical components in air particulate matter

3.1 Actively discharged ascospores (AAS) and basidiospores (ABS)

The abundance of fungal spores in the air is highly variable, and is dependent upon location, season, time of day, and weather. Air masses with low concentrations of spores can be intercepted by plumes with very high concentrations (Chatterjee and

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Hargreave, 1974; Burch and Levetin, 2002). Specific information on the atmospheric abundance of AAS and ABS is very limited. In a comprehensive literature search we found some data from ground based aerosol investigations, but none from airborne sampling.

5 Table 2 summarizes ambient concentrations of AAS (a) and ABS (b) reported in earlier studies, and the results of our microscopic investigations of aerosol filter samples collected in the tropical rainforest of Amazonia. Overall, the concentrations range from zero to $\sim 10^4 \text{ m}^{-3}$, with exceptional maximum values up to $\sim 10^6 \text{ m}^{-3}$ observed for AAS during the harvesting of barley. Most of the concentrations reported for AAS and ABS, including the few data available from tropical regions (Brazil, Mexico, Taiwan), range between 10^3 m^{-3} and 10^4 m^{-3} .

These data for AAS and ABS are consistent with recent studies investigating total concentrations of fungal spores in alpine air ($\sim 10^3 \text{ m}^{-3}$; Mt. Rax, Austria) and urban air ($8\text{--}26 \times 10^3 \text{ m}^{-3}$; Vienna, Austria), corresponding to 2–6% of the organic carbon fraction and up to 1.3% of the total mass of air particulate matter (Bauer et al., 2002, 2005). In rural air over an agricultural region, Burch and Levetin (2002) recorded concentrations of total fungal spores in the range of $2\text{--}17 \times 10^4 \text{ m}^{-3}$ (Bixby/Tulsa, USA). They also reported that passively discharged fungal spores were generally enhanced during warm, dry weather conditions, whereas AAS and ABS tended to be more concentrated during wet or humid conditions, such as those at night and in the early morning. Precipitation appeared to be required for the release of spores from many AAM, and AAS concentrations usually increased during and after rainstorms. The release and resultant airborne concentrations of ABS, on the other hand, appeared to be more directly correlated with relative humidity rather than precipitation (Ingold, 1971; Chatterjee and Hargreave, 1974; Burch and Levetin, 2002).

25 Air samples used in our investigations were collected at the beginning of the dry season at Balbina, Amazonia, Brazil, ($1^\circ 55' \text{ S}$, $59^\circ 24' \text{ W}$, 174 m above sea level) on a pasture site adjacent to pristine tropical rainforest. Samples for microscopic examination were taken with a rotating impactor and with an isokinetic 2-stage jet impactor posi-

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

tioned 2 m above the ground. Air samples for the determination of inorganic ions in fine particulate matter ($\leq 2 \mu\text{m}$) and coarse particles ($2\text{--}10 \mu\text{m}$) were taken with two-stage stacked filter units (SFU). Sugars and sugar alcohols were determined in aerosol particle samples collected with a dichotomous high-volume (HiVol) sampler: fine ($\leq 2.5 \mu\text{m}$) and coarse ($\geq 2.5 \mu\text{m}$). Both the SFU and the HiVol samplers were positioned 4 m above the ground (Graham et al., 2003a; Graham et al., 2003b; Moura et al., 2004).

AAS and ABS were determined by detailed microscopic investigation of two exemplary samples collected with the jet impactor on 22 July 2001 (local time of sampling: 09:10–09:48 and 23:55–01:05). The samples were mounted and directly observed with a Nikon 80i light microscope at up to 1500x magnification. Fungal spore types were identified based on their morphology in 200 fields of view for each sample. Counts were expressed per cubic meter of air sampled.

Fungal spores ($2\text{--}20 \mu\text{m}$) were generally most abundant in night-time samples when the relative humidity was close to 100%, whereas the concentration of larger fern spores and pollen was typically higher in day-time samples (Graham et al., 2003a). The night-time concentrations were $\sim 7400 \text{ m}^{-3}$ for AAS and $\sim 12800 \text{ m}^{-3}$ for ABS ($\sim 3600 \text{ m}^{-3}$ from rust fungi and $\sim 9150 \text{ m}^{-3}$ from smut fungi); the day-time concentrations were $\sim 3000 \text{ m}^{-3}$ for AAS and $\sim 1800 \text{ m}^{-3}$ for ABS (almost exclusively from rust fungi). The results are consistent with the general trends and concentrations of AAS, ABS, and total fungal spores observed in earlier investigations (as outlined above) and in a recent study of colony-forming spores sampled from a tropical rainforest in Australia (Gilbert and Reynolds, 2005).

3.2 Carbohydrates: mannitol, glucose, and fructose

Table 3 gives an overview of the concentrations reported for the sugar alcohol mannitol ($\text{C}_6\text{H}_{14}\text{O}_6$) in atmospheric aerosols. At extratropical locations, the average concentrations of mannitol were $1\text{--}11 \text{ ng m}^{-3}$ for particles $\leq 2.5 \mu\text{m}$ and $0\text{--}220 \text{ ng m}^{-3}$ for particles $\geq 2.5 \mu\text{m}$. In aerosol samples from Amazonia and Rondônia (Brazil), average mannitol concentrations were 2–3 times higher than at extratropical locations: $8\text{--}26 \text{ ng m}^{-3}$

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

for particles $\leq 2.5 \mu\text{m}$, and 29–112 ng m^{-3} for particles $\geq 2.5 \mu\text{m}$. Investigations with separate day-time and night-time samples of particles $\geq 2.5 \mu\text{m}$ showed that the night-time concentrations of mannitol were higher by factors of 2–3 (Graham et al., 2002, 2003b; Claeys et al., 2004). Recent investigations with an 11-stage MOUDI aerosol im-

5 pactor showed that the mass size distribution of mannitol in tropical rainforest aerosols (Rondônia, Brazil) exhibited a maximum at particle diameters around $5 \mu\text{m}$. The maximum was particularly pronounced (up to three orders of magnitude higher than the lowest values of the size distribution function) during nights of the dry season and throughout the transition and wet seasons (Decesari et al., 2006; Fuzzi et al., 2006b).

10 In the wet season the total aerosol mass size distribution function was also dominated by a pronounced maximum at particle diameters around $5 \mu\text{m}$ (Fuzzi et al., 2006b).

Table 4 gives an overview of the atmospheric concentrations observed for the hexose sugars, glucose and fructose ($\text{C}_6\text{H}_{12}\text{O}_6$). In contrast to mannitol, the glucose and fructose concentrations determined in samples of air particulate matter from Amazonia and Rondônia (Brazil), were not higher than at extratropical locations: 1–49 ng m^{-3}

15 ($\leq 2.5 \mu\text{m}$) and 3–146 ng m^{-3} ($\geq 2.5 \mu\text{m}$) at tropical locations; 10–15 ng m^{-3} ($\leq 2.5 \mu\text{m}$) and 1–270 ng m^{-3} ($\geq 2.5 \mu\text{m}$) at extratropical locations. Moreover, studies with separate day-time and night-time sampling at tropical sites showed a diurnal cycle opposite to that of mannitol: glucose and fructose concentrations were strongly enhanced during

20 day-time (up to 50 times higher than at night) (Graham et al., 2003b).

3.3 Inorganic Ions: potassium and chloride

Tables 5 and 6 give an overview of potassium and chloride ion concentrations in atmospheric aerosols observed during the wet season at various locations in Amazonia. The concentrations of potassium were typically in the range of 24–220 ng m^{-3} for particles $\leq 2 \mu\text{m}$ and 14–270 ng m^{-3} for particles in the size range of 1–15 μm , respectively,

25 and night-time concentrations generally exceeded day-time concentrations (Graham et al., 2003a; Fuzzi et al., 2006b). The chloride concentrations were in the range of

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

5–65 ng m⁻³ for particles ≤2 μm and 8–155 ng m⁻³ for particles with diameters of 2–15 μm, respectively.

3.4 Total air particulate matter

Table 7 lists total particle mass concentrations recorded during the wet season at various locations in Amazonia. Long-term average values for the particle size range of 2–10 μm were typically 5–16 μg m⁻³ (Artaxo et al., 1990; Formenti et al., 2001; Guyon et al., 2003). Studies with separate day- and night-time sampling showed that particle mass concentrations were 2–4 times higher at night (Graham et al., 2003a; Fuzzi et al., 2006b).

4 Contribution of AAM and ABM emissions to the mass and chemical composition of Amazonian rainforest aerosols

To calculate an estimate of the relative contribution of fungal emissions to the chemical composition of coarse air particulate matter (particle diameters 1–2 μm to 10–15 μm) in the tropical rainforest of Amazonia during the wet season, we used the parameters listed in Table 8, which have been derived from the literature (Webster et al., 1995; Trail et al., 2005). For the average mass of AAS we assumed a value of 200 pg for AAS, corresponding to a volume equivalent diameter of ~7 μm and density of ~1 g cm⁻³ (Trail et al., 2005). For ABS we assumed an average mass of 65 pg, corresponding to a volume equivalent diameter of ~5 μm and density of ~1 g cm⁻³ (Buller, 1909; Ingold, 1971; Lin and Li, 1996; Ingold, 2001b; Wu et al., 2004) and consistent with the maximum of mannitol and PM size distributions observed in tropical rainforest aerosols during the wet season (Fuzzi et al., 2006b). This is a lower estimate compared to the 840 pg per ABS of *I. perplexans* reported by Turner and Webster (1991), which would correspond to a volume equivalent diameter of ~12 μm at ~1 g cm⁻³. For AAS, the number of spores per ascus can vary over a range of about 1–100. Nevertheless, an

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

average number of 8 spores per ascus has been determined for the majority of AAM used in our calculations (Ingold, 1971).

By multiplication of the parameters outlined above with the measured number concentrations of AAS and ABS, we obtained the mass concentration estimates listed in Table 9 and illustrated in Figs. 1–4.

For mannitol (Fig. 1), the estimated fungal emissions are dominated by ABS and account for 100% of the night-time, 35% of the day-time, and 80% of the average concentrations, which have been determined in two independent measurements at the same location and period of time (Balbina: 19–28 July 2001, (Graham et al., 2003b); 25–28 July 2001, (Claeys et al., 2004); particle diameters $\geq 2.5 \mu\text{m}$).

For the hexoses (Fig. 2), the fungal emission estimate (related to ABS only) exceeds the measured night-time concentrations of glucose and fructose by a factor of 10. During day-time the estimated fungal emissions would account for only $\sim 10\%$, and averaged over 24 hours they would account for $\sim 60\%$ of the observed concentrations.

For potassium (Fig. 3), the estimated fungal emissions (related to AAS only) account for $\sim 60\%$ of the average concentration measured at the same location and period of time (Balbina: 16–28 July 2001, (Graham et al., 2003a); particle diameters $2\text{--}10 \mu\text{m}$; separate day- and night-time values not available). Compared to measurement data from a different place and time during the wet season in Amazonia (FNS: Fazenda Nossa Senhora Aparecida, near Ouro Preto do Oeste, Rondônia) (Fuzzi et al., 2006b), the day- and night-time estimates would account for practically all of the potassium in the investigated aerosol particle size range ($1\text{--}10 \mu\text{m}$) and are consistent with the observed diurnal cycle.

For chloride (Tables 6 and 9), the estimated fungal emissions (related to AAS only) account for $\sim 15\%$ of the average concentration measured at the same location and period of time (Balbina: 16–28 July 2001, (Graham et al., 2003a); particle diameters $2\text{--}10 \mu\text{m}$; separate day- and night-time values not available).

For total mass of particulate matter (Fig. 4), the estimated emissions by actively spore discharging fungi are dominated by the spores rather than the solutes (solute

Contribution of fungi
to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

mass fraction only 5–10%) and account for ~45% of the night-time, ~25% of the day-time, and ~35% of the average concentrations measured at the same location and period of time (Balbina: 22–25 July 2001, (Graham et al., 2003a); particle diameters 2–10 μm). Compared to measurement data from FNS (Fuzzi et al., 2006b), the estimated proportion of fungal emissions in particles sized 1–10 μm in diameter would be slightly lower at night, higher during the day, and similar on average.

5 Global emission rate of ABS

As outlined above (Sect. 3.1, Table 2), the knowledge about the abundance and activity of fungi in the global biosphere is very limited, and regional or global estimates for the emission rate and flux of actively-discharged fungal spores are not yet available in the literature.

Here, we calculate a first estimate for the global average emission rate of ABS over land surfaces based on the following first-order approximations and assumptions:

1) The abundance of mannitol in the atmosphere is assumed to be dominated by emissions from ABM, which is supported by the literature data and results outlined above (Table 2: similar abundance of AAS and ABS; Table 8: higher amount of mannitol emitted with one ABS per Buller's drop compared to eight AAS per ascus; Table 9 and Fig. 1: consistency of exemplary calculations).

2) The literature-derived value of 5 pg mannitol emitted per ABS (Table 8) is assumed to be representative for ABM, which is supported by the results outlined above (Table 9 and Fig. 1: consistency of exemplary calculations).

3) The average value of mannitol concentrations reported for PM with particle diameters up to 10 μm or more at extratropical measurement locations (25 ng m^{-3} , Table 3, lines 9–15) is assumed to be representative for a well-mixed continental boundary layer (CBL) with an average height of 1 km (Seinfeld and Pandis, 1998). The following evidence supports these assumptions as conservative: significantly higher mannitol concentrations reported from tropical regions (Table 3); significantly higher and well-mixed

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

day-time CBLs in tropical regions (Graham et al., 2003b); observation of elevated spore concentrations in the upper part of the CBL (Meier and Artschwager, 1938; Linskens and Jorde, 1986).

4) The average size and atmospheric residence time of ABS are assumed to be on the order of $5\text{ }\mu\text{m}$ and 1 day, respectively, which is supported by the literature data and results outlined above (Table 9 and Fig. 4: consistency of exemplary calculations) and by the basic concepts of atmospheric aerosol cycling (rapid sedimentation and wet deposition of coarse particles).

Dividing the average mannitol concentration of 25 ng m^{-3} by 5 pg (amount of mannitol emitted per ABS) we obtain a value of $5\times 10^3\text{ m}^{-3}$ as a first-order estimate for the global average number concentration of ABS in the continental boundary layer, which is consistent with the observations summarized in Table 2b and discussed in Sect. 3.1. Multiplication with an average spore mass of 65 pg yields a value of an average contribution of $0.3\text{ }\mu\text{g m}^{-3}$ to the concentration of air particulate matter, which is also consistent with the observations reported in Sect. 3.1. As demonstrated above, the total mass concentration of actively discharged spores and related substances observed in tropical rainforest regions during the wet season are significantly higher, supporting the above values as conservative estimates.

Multiplication of the average number concentration with an average CBL height of 1000 m and division by an average residence time of 1 day yields an estimate of $\sim 5\times 60\text{ m}^{-2}\text{ s}^{-1}$ for the globally averaged land surface emission flux of ABS. By multiplication with an average spore mass of 65 pg , the global land surface area of $1.5\times 10^{14}\text{ m}^2$ and the duration of one year we obtain an estimate of $\sim 17\text{ Tg yr}^{-1}$ for the global emission rate of ABS.

For comparison: current estimates of the rates of emission and formation of other types of air particulate matter are $\sim 47\text{ Tg yr}^{-1}$ for anthropogenic primary organic aerosols (POA: 35 Tg yr^{-1} from vegetation fires, 9 Tg yr^{-1} from biofuel combustion, 3 Tg yr^{-1} from fossil fuel combustion) and $12\text{--}70\text{ Tg yr}^{-1}$ for secondary organic aerosols (SOA: mostly from oxidation of biogenic terpenes; Kanakidou et al., 2005).

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

6 Summary and conclusions

In this study we have gathered and summarized qualitative and quantitative information on the atmospheric abundance and emission of spores and related chemical compounds from AAM and ABM. These primary biogenic components of coarse air particulate matter (characteristic size range 1–10 μm) may influence the formation of clouds and precipitation as cloud condensation and ice nuclei, and they affect the spread and reproduction of organisms in the biosphere. The effects of fungal emissions might be particularly important in tropical regions where both physicochemical processes in the atmosphere and biological activity at the Earth's surface are particularly intense.

Measurements and budget calculations based on our investigations in Amazonia (Balbina, Brazil, July 2001) indicate that the forcible discharge of fungal spores may account for a large proportion of coarse air particulate matter in tropical rainforest regions during the wet season. For the particle diameter range of 1–10 μm the estimated proportions are ~25% during day-time, ~45% at night, and ~35% on average. For the sugar alcohol mannitol, the budget calculations indicate that it may be used as a molecular tracer for ABS, that the literature-derived emission ratio of about 5 pg per ABS may be taken as a representative average, and that the ABM emissions may account for most of its atmospheric abundance and can explain the observed diurnal cycle (higher abundance at night). ABM emissions of hexose carbohydrates might also account for a significant proportion of glucose and fructose in aerosols, but the literature-derived emission factors are not consistent with the observed diurnal cycle (lower abundance at night). AAM emissions appear to account for a large proportion of potassium in aerosols over tropical rainforest regions during the wet season, and they can also explain the observed diurnal cycle (higher abundance at night). The results of our investigations and budget calculations for tropical rainforest aerosols are consistent with measurements performed at other locations in Amazonia.

Based on the average abundance of mannitol in air particulate matter, which is consistent with the above emission ratio and observed abundance of ABS, we have also

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

calculated a value of $\sim 17 \text{ Tgyr}^{-1}$ as a first estimate for the global average emission rate of ABS over land surfaces. Comparison with estimated rates of emission and formation of other major types of organic air particulate matter ($\sim 47 \text{ Tgyr}^{-1}$ of anthropogenic POA; $12\text{--}70 \text{ Tgyr}^{-1}$ of SOA) indicates that the emissions from actively

spore-discharging fungi should be taken into account as a significant source of organic air particulate matter. Their effects might be particularly important in tropical regions, where both physicochemical processes in the atmosphere and biological activity at the Earth's surface are particularly intense, and where the abundance of fungal spores and related chemical compounds are typically higher than in extratropical regions.

For further insight and understanding of seasonal and regional variations, vertical profiles, and long-range transport of fungal spores and related aerosol components, additional ground-based and airborne measurements of these species will be required. Moreover, a reliable assessment of the overall role of bioaerosols in the climate system and of the relative importance of fungal emissions will require similar investigations for other abundant primary biogenic aerosol particles such as pollen and bacteria.

Acknowledgements. This study is based on results from the Large-Scale Atmosphere-Biosphere Experiment in Amazonia (LBA) and was funded by the Max Planck Society. P. Taylor acknowledges financial support by a grant from the Southern California Environmental Health Sciences Center (NIEHS 5P30 ES07048), a Boswell Fellowship from Caltech and the Huntington Medical Research Institute. P. Taylor also thanks R. C. Flagan, Caltech, and E. Newbigin, University of Melbourne. Special thanks are due to C. Morris for helpful comments, and to T. W. Andreae for help with the preparation of the manuscript.

References

- Adams, K. F., Hyde, H. A., and Williams, D. A.: Woodlands as a source of allergens with special reference to basidiospores, *Acta Allergologica*, 23, 265–281, 1968.
- Andreae, M. O., Artaxo, P., Brandão, C., Carswell, F. E., Ciccioli, P., da Costa, A. L., Culf, A. D., Esteves, J. L., Gash, J. H. C., Grace, J., Kabat, P., Lelieveld, J., Malhi, Y., Manzi, A. O., Meixner, F. X., Nobre, A. D., Nobre, C., Ruivo, M. d. L. P., Silva-Dias, M. A., Stefani,

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- P., Valentini, R., von Jouanne, J., and Waterloo, M. J.: Biogeochemical cycling of carbon, water, energy, trace gases and aerosols in Amazonia: The LBA-EUSTACH experiments, J. Geophys. Res., 107, 8066, doi:10.1029/2001JD000524, 2002.
- Andreae, M. O. and Crutzen, P. J.: Atmospheric aerosols: Biogeochemical sources and role in atmospheric chemistry, Science, 276, 1052–1058, 1997.
- Artaxo, P. and Hansson, H.-C.: Size distribution of biogenic aerosol particles from the Amazon basin, Atmos. Environ., 29, 393–402, 1995.
- Artaxo, P., Maenhaut, W., Storms, H., and Grieken, R. V.: Aerosol characteristics and sources for the Amazon Basin during the wet season, J. Geophys. Res., 95, 16 971–16 986, 1990.
- Artaxo, P., Martins, J. V., Yamasoe, M. A., Procopio, A. S., Pauliquevis, T. M., Andreae, M. O., Guyon, P., Gatti, L. V., and Leal, A. M. C.: Physical and chemical properties of aerosols in the wet and dry seasons in Rondonia, Amazonia, J. Geophys. Res., 107, 8081, doi:10.1029/2001JD000666, 2002.
- Bauer, H., Kasper-Giebl, A., Loflund, M., Giebl, H., Hitzengerger, R., Zibuschka, F., and Puxbaum, H.: The contribution of bacteria and fungal spores to the organic carbon content of cloud water, precipitation and aerosols, Atmos. Res., 64, 109–119, 2002.
- Bauer, H., Weinke, G., Scheller, L., Berger, A., Kasper-Giebl, A., Puxbaum, H., Vermeylen, R., Claeys, M., and Maenhaut, W.: Contribution of bioaerosols to organic carbon in urban-fringe aerosols, European Aerosol Conference 2005, 2005.
- Beauford, W., Barber, J., and Barringer, A. R.: Heavy metal release from plants into the atmosphere, Nature, 256, 35–37, 1975.
- Brown, J. K. M. and Hovmoller, M. S.: Epidemiology – Aerial dispersal of pathogens on the global and continental scales and its impact on plant disease, Science, 297, 537–541, 2002.
- Buller, A. H. R.: Researches on fungi, Longmans, Green and Co., London, 1909.
- Buller, A. H. R.: Researches on fungi, Longmans, Green and Co., London, 1909–1950.
- Buller, A. H. R.: Die Erzeugung und Befreiung der Sporen bei *Coprinus sterquilinus*, Jahrbücher für wissenschaftliche Botanik, 56, 299–329, 1915.
- Buller, A. H. R.: Researches on fungi, Longmans, Green and Co., London, 1922.
- Buller, A. H. R. and Vanterpool, T. C.: Violent spore-discharge in *Tilletia tritici*, Nature, 116, 934–935, 1925.
- Burch, M. and Levetin, E.: Effects of meteorological conditions on spore plumes, Int. J. Biometeorol., 46, 107–117, 2002.
- Calderon, C., Lacey, J., McCartney, H. A., and Rosas, I.: Seasonal and diurnal-variation of

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- airborne basidiomycete spore concentrations in Mexico-City, Grana, 34, 260–268, 1995.
- Carvalho, A., Pio, C., and Santos, C.: Water-soluble hydroxylated organic compounds in German and Finnish aerosols, Atmos. Environ., 37, 1775–1783, 2003.
- Chatterjee, J. and Hargreave, F. E.: Atmospheric pollen and fungal spores in Hamilton in 1972
 5 estimated by the Hirst automatic volumetric spore trap, Can. Medical Assoc. J., 110, 659–663, 1974.
- Claeys, M., Graham, B., Vas, G., Wang, W., Vermeylen, R., Pashynska, V., Cafmeyer, J., Guyon, P., Andreae, M. O., Artaxo, P., and Maenhaut, W.: Formation of secondary organic aerosols through photooxidation of isoprene, Science, 303, 1173–1176, 2004.
- 10 Couch, J. N.: A new *Conidiobulus* with sexual reproduction, Am. J. Botany, 26, 119–130, 1939.
- Cox, C. S. and Wathes, C. M.: Bioaerosol Handbook, CRC Lewis Publishers, Boca Raton, 1995.
- Decco, M. L., Wendland, B. I., and O'Connell, E. J.: Volumetric assessment of airborne pollen and spore levels in Rochester, Minnesota, 1992 through 1995, Mayo Clinic Proceedings, 73, 225–229, 1998.
- 15 Decesari, S., Fuzzi, S., Facchini, M. C., Mircea, M., Emblico, L., Cavalli, F., Maenhaut, W., Chi, X., Schkolnik, G., Falkovich, A., Rudich, Y., Claeys, M., Pashynska, V., Vas, G., Kourtchev, I., Vermeylen, R., Hoffer, A., Andreae, M. O., Tagliavini, E., Moretti, F., and Artaxo, P.: Characterization of the organic composition of aerosols from Rondonia, Brazil, during the LBA-SMOCC 2002 experiment and its representation through model compounds, Atmos. Chem. Phys., 6, 375–402, 2006.
- 20 Dingle, A. N.: Pollens as condensation nuclei, Journal de Recherches Atmosphériques, 2, 231–237, 1966.
- Dusek, U., Frank, G. P., Hildebrandt, L., Curtius, J., Schneider, J., Walter, S., Chand, D., Drewnick, F., Hings, S., Jung, D., Borrmann, S., and Andreae, M. O.: Size matters more than chemistry for cloud-nucleating ability of aerosol particles, Science, 312, 1375–1378, 2006.
- 25 Echalar, F., Artaxo, P., Martins, J. V., Yamasoe, M., Gerab, F., Maenhaut, W., and Holben, B.: Long-term monitoring of atmospheric aerosols in the Amazon Basin: Source identification and apportionment, J. Geophys. Res., 103, 31 849–31 864, 1998.
- 30 Ehrenberg, C. G.: Neue Beobachtungen über blutartige Erscheinungen in Aegypten, Arabien und Sibirien, nebst einer Uebersicht und Kritik der früher bekannten, Annalen der Physik und Chemie, 94, 477–514, 1830.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Fernando, W. G. D., Miller, J. D., Seaman, W. L., Seifert, K., and Paulitz, T. C.: Daily and seasonal dynamics of airborne spores of *Fusarium graminearum* and other *Fusarium* species sampled over wheat plots, *Can. J. Botany*, 78, 497–505, 2000.
- Fischer, M., Cox, J., Davis, D. J., Wagner, A., Taylor, R., Huerta, A. J., and Money, N. P.: New information on the mechanism of forcible ascospore discharge from *Ascobolus immersus*, *Fungal Genetics and Biology*, 41, 972–972, 2004.
- Fish, B. R.: Electrical generation of natural aerosols from vegetation, *Science*, 175, 1239–1240, 1972.
- Formenti, P., Andreae, M. O., Lange, L., Roberts, G., Cafmeyer, J., Rajta, I., Maenhaut, W., Holben, B. N., Artaxo, P. and Lelieveld, J.: Saharan dust in Brazil and Suriname during the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) - Cooperative LBA Regional Experiment (CLAIRE) in March 1998, *J. Geophys. Res.*, 106, 14 919–14 934, 2001.
- Frankland, A. W. and Gregory, P. H.: Allergenic and agricultural implications of airborne ascospore concentrations from a fungus, *Didymella exitialis*, *Nature*, 245, 336–337, 1973.
- Franze, T., Weller, M. G., Niessner, R., and Pöschl, U.: Protein nitration by polluted air, *Environ. Sci. Technol.*, 39, 1673–1678, 2005.
- Fuzzi, S., Andreae, M. O., Huebert, B. J., Kulmala, M., Bond, T. C., Boy, M., Doherty, S. J., Guenther, A., Kanakidou, M., Kawamura, K., Kerminen, V. M., Lohmann, U., Russell, L. M., and Pöschl, U.: Critical assessment of the current state of scientific knowledge, terminology, and research needs concerning the role of organic aerosols in the atmosphere, climate, and global change, *Atmos. Chem. Phys.*, 6, 2017–2038, 2006a.
- Fuzzi, S., Decesari, S., Facchini, M. C., Cavalli, F., Emblico, L., Mircea, M., Andreae, M. O., Trebs, I., Hoffer, A., Guyon, P., Artaxo, P., Rizzo, L. V., Lara, L. L., Pauliquevis, T., Maenhaut, W., Raes, N., Chi, X., Mayol-Bracero, O. L., Soto-García, L. L., Claeys, M., Kourtchev, I., Rissler, J., Swietlicki, E., Tagliavini, E., Schkolnik, G., Falkovich, A. H., Rudich, Y., Fisch, G., and Gatti, L. V.: Overview of the inorganic and organic composition of size-segregated aerosol in Rondônia, Brazil, from the biomass burning period to the onset of the wet season, *J. Geophys. Res.*, in press, 2006b.
- Gilbert, G. S. and Reynolds, D. R.: Nocturnal fungi: Airborne spores in the canopy and understory of a tropical rain forest, *Biotropica*, 37, 462–464, 2005.
- Górny, R. L., Reponen, T., Willeke, K., Schmechel, D., Robine, E., Boissier, M., and Grinshpun, S. A.: Fungal fragments as indoor air biocontaminants, *Appl. Environ. Microbiol.*, 68, 3522–3531, 2002.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Graham, B., Guyon, P., Maenhaut, W., Taylor, P. E., Ebert, M., Matthias-Maser, S., Mayol-Bracero, O. L., Godoi, R. H. M., Artaxo, P., Meixner, F. X., Moura, M. A. L., Rocha, C., Van Grieken, R., Glovsky, M. M., Flagan, R. C., and Andreae, M. O.: Composition and diurnal variability of the natural Amazonian aerosol, *J. Geophys. Res.*, 108, 4765, doi:10.1029/2003JD004049, 2003a.
- Graham, B., Guyon, P., Taylor, P. E., Artaxo, P., Maenhaut, W., Glovsky, M. M., Flagan, R. C., and Andreae, M. O.: Organic compounds present in the natural Amazonian aerosol: Characterization by gas chromatography-mass spectrometry, *J. Geophys. Res.-Atmos.*, 108, 4766, doi:10.1029/2003JD003990, 2003b.
- Graham, B., Mayol-Bracero, O. L., Guyon, P., Roberts, G. C., Decesari, S., Facchini, M. C., Artaxo, P., Maenhaut, W., Koll, P., and Andreae, M. O.: Water-soluble organic compounds in biomass burning aerosols over Amazonia – 1. Characterization by NMR and GC-MS, *J. Geophys. Res.*, 107, 8047, doi:10.1029/2001JD000336, 2002.
- Gregory, P. H.: Distribution of airborne pollen and spores and their long distance transport, *Pure and Applied Geophysics*, 116, 309–315, 1978.
- Gregory, P. H. and Hirst, J. M.: Possible role of basidiospores as air-borne allergens, *Nature*, 170, 414, 1952.
- Griffin, D. W., Garrison, V. H., Herman, J. R., and Shinn, E. A.: African desert dust in the Caribbean atmosphere: Microbiology and public health, *Aerobiologia*, 17, 203–213, 2001.
- Guyon, P., Graham, B., Roberts, G. C., Mayol-Bracero, O. L., Maenhaut, W., Artaxo, P., and Andreae, M. O.: In-canopy gradients, composition, sources, and optical properties of aerosol over the Amazon forest, *J. Geophys. Res.*, 108, 4591, doi:10.1029/2003JD003465, 2003.
- Hamilton, W. D. and Lenton, T. M.: Spora and Gaia: How microbes fly with their clouds, *Ethology Ecology and Evolution*, 10, 1–16, 1998.
- Hasnain, S. M., Fatima, K., Al-Frayh, A., and Al-Sedairy, S. T.: Prevalence of airborne basidiospores in three coastal cities of Saudi Arabia, *Aerobiologia*, 21, 139–145, 2005.
- Helbling, A., Brander, K. A., Horner, W. E. and Lehrer, S. B.: Allergy to basidiomycetes, in: *Fungal Allergy and Pathogenicity*, edited by: Breitenbach, M., Cramer, R., and Lehrer, S. B., Karger, Basel, 81, 28–47, 2002.
- Hock, J., Kranz, J., and Renfro, B. L.: Studies on the epidemiology of the tar spot disease complex of maize in Mexico, *Plant Pathology*, 44, 490–502, 1995.
- Hong, C. X. and Michailides, T. J.: Effect of temperature on the discharge and germination of ascospores by apothecia of *Monilinia fructicola*, *Plant Disease*, 82, 195–202, 1998.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Imshenetsky, A. A., Lysenko, S. V., and Kazakov, G. A.: Upper boundary of the biosphere, Appl. Environ. Microbiol., 35, 1–5, 1978.
- Inch, S., Fernando, W. G. D., and Gilbert, J.: Seasonal and daily variation in the airborne concentration of *Gibberella zeae* (Schw.) Petch spores in Manitoba, Canadian Journal of Plant Pathology-Revue Canadienne De Phytopathologie, 27, 357–363, 2005.
- Ingold, C. T.: Fungal spores. Their liberation and dispersal, Clarendon Press, Oxford, 1971.
- Ingold, C. T.: Active liberation of reproductive units in terrestrial fungi, Mycologist, 13, 113–116, 1999.
- Ingold, C. T.: Singling of meiospores, Mycologist, 15, 86–87, 2001a.
- Ingold, C. T.: Range in size and form of basidiospores and ascospores, Mycologist, 15, 165–166, 2001b.
- Ion, A. C., Vermeylen, R., Kourtchev, I., Cafmeyer, J., Chi, X., Gelencsér, A., Maenhaut, W., and Claeys, M.: Polar organic compounds in rural PM_{2.5} aerosols from K-pusztá, Hungary, during a 2003 summer field campaign: Sources and diel variations, Atmos. Chem. Phys., 5, 1805–1814, 2005.
- Jaenicke, R.: Abundance of cellular material and proteins in the atmosphere, Science, 308, 73–73, 2005.
- Kanakidou, M., Seinfeld, J. H., Pandis, S. N., Barnes, I., Dentener, F. J., Facchini, M. C., Van Dingenen, R., Ervens, B., Nenes, A., Nielsen, C. J., Swietlicki, E., Putaud, J. P., Balkanski, Y., Fuzzi, S., Horth, J., Moortgat, G. K., Winterhalter, R., Myhre, C. E. L., Tsigaridis, K., Vignati, E., Stephanou, E. G., and Wilson, J.: Organic aerosol and global climate modelling: a review, Atmos. Chem. Phys., 5, 1053–1123, 2005.
- Kourtchev, I., Ruuskanen, T., Maenhaut, W., Kulmala, M., and Claeys, M.: Observation of 2-methyltetrols and related photo-oxidation products of isoprene in boreal forest aerosols from Hyytiälä, Finland, Atmos. Chem. Phys., 5, 2761–2770, 2005a.
- Kourtchev, I., Warnke, J., Maenhaut, W., Hoffmann, T., and Claeys, M.: Poster presentation: Characterisation of polar organic compounds in PM_{2.5} aerosols from Jülich, Germany, European Aerosol Conference 2005, Ghent, Belgium, 2005b.
- Levetin, E.: Studies on airborne basidiospores, Aerobiologia, 6, 177–180, 1990.
- Li, D. W. and Kendrick, B.: A year-round outdoor aeromycological study in Waterloo, Ontario, Canada, Grana, 34, 199–207, 1995.
- Lin, W. H. and Li, C. S.: Size characteristics of fungus allergens in the subtropical climate, Aerosol Sci. Technol., 25, 93–100, 1996.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Linskens, H. F. and Jorde, W.: Pollentransport in großen Höhen - Beobachtungen während der Fahrt mit einem Gasballon, *Allergologie*, 9, 55–58, 1986.
- Lohmann, U. and Feichter, J.: Global indirect aerosol effects: A review, *Atmos. Chem. Phys.*, 5, 715–737, 2005.
- 5 Maenhaut, W., Fernandez-Jimenez, M.-T., Rajta, I., and Artaxo, P.: Two-year study of atmospheric aerosols in Alta Floresta, Brazil: Multielemental composition and source apportionment, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 189, 243–248, 2002.
- Matthias-Maser, S. and Jaenicke, R.: Identification and size distribution of biological aerosol particles with radius $>0.2\ \mu\text{m}$, in: *Nucleation and Atmospheric Aerosols*, edited by: Fukuta, N. and Wagner, P. E., A. DEEPAK Publishing, 413–415, 1992.
- 10 McCarthy, M.: Dust clouds implicated in spread of infection, *Lancet*, 358, 478–478, 2001.
- McFiggans, G., Artaxo, P., Baltensperger, U., Coe, H., Facchini, M. C., Feingold, G., Fuzzi, S., Gysel, M., Laaksonen, A., Lohmann, U., Mentel, T. F., Murphy, D. M., O'Dowd, C. D., Snider, J. R., and Weingartner, E.: The effect of physical and chemical aerosol properties on warm cloud droplet activation, *Atmos. Chem. Phys.*, 6, 2593–2649, 2006.
- 15 Meier, F. C.: Collecting micro-organisms from the Arctic atmosphere. With field notes and material by Charles A. Lindberg., *The Scientific Monthly*, 40, 5–20, 1935.
- Meier, F. C. and Artschwager, E.: Airplane collection of sugar-beet pollen, *Science*, 88, 507–508, 1938.
- 20 Meredith, D. S.: Significance of spore release and dispersal mechanisms in plant disease epidemiology, *Ann. Rev. Phytopathol.*, 11, 313–342, 1973.
- Miguel, A. G., Cass, G. R., Glovsky, M. M., and Weiss, J.: Allergens in paved road dust and airborne particles, *Environm. Sci. Technol.*, 33, 4159–4168, 1999.
- 25 Moura, M. A. L., Meixner, F. X., Trebs, I., Lyra, R. F. F., Andreae, M. O., and Filho, M. F. N.: Observational evidence of lake breezes at Balbina lake (Amazonas, Brazil) and their effect on ozone concentrations., *Acta Amazonica*, 34, 605–611, 2004.
- Newson, R., Strachan, D., Corden, J., and Millington, W.: Fungal and other spore counts as predictors of admissions for asthma in the Trent region, *Occupational and Environmental Medicine*, 57, 786–792, 2000.
- 30 Pady, S. M., Peturson, B., and Green, G. J.: Arctic aerobiology. III. The presence of spores of cereal pathogens on slides exposed from airplanes in 1947, *Phytopathology*, 40, 632–641, 1950.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Page, R. M.: Sporangium discharge in *Pilobolus*: A photographic study, *Science*, 146, 925–927, 1964.
- Pashynska, V., Vermeylen, R., Vas, G., Maenhaut, W., and Claeys, M.: Developement of a gas chromatographic/ion trap mass spectrometric method for the determination of levoglucosan and saccharidic compounds in atmospheric aerosols. Application to urban aerosols, *J. Mass Spectrometry*, 37, 1249–1257, 2002.
- Pasteur, L.: Expériences relatives aux générations dites spontanées, *Comptes Rendus hebdomadaires des Séances de l'Académie des Sciences Paris*, 50, 303–307, 1860a.
- Pasteur, L.: Suite à une précédente communication relative aux générations dites spontanées, *Comptes Rendus hebdomadaires des Séances de l'Académie des Sciences Paris*, 51, 675–678, 1860b.
- Paulitz, T. C.: Diurnal release of ascospores by *Gibberella zeae* in inoculated wheat plots, *Plant Disease*, 80, 674–678, 1996.
- Pöschl, U.: Atmospheric aerosols: Composition, transformation, climate and health effects, *Angewandte Chemie-International Edition*, 44, 7520–7540, 2005.
- Prados-Ligero, A. M., Melero-Vara, J. M., Corpas-Hervias, C., and Basallote-Ureba, M. J.: Relationships between weather variables, airborne spore concentrations and severity of leaf blight of garlic caused by *Stemphylium vesicarium* in Spain, *European Journal of Plant Pathology*, 109, 301–310, 2003.
- Pringle, A., Patek, S. N., Fischer, M., Stolze, J., and Money, N. P.: The captured launch of a ballistospore, *Mycologia*, 97, 866–871, 2005.
- Proctor, B. E.: The microbiology of the upper air. I., *Proceedings of the American Academy of Arts and Sciences*, 69, 314–340, 1934.
- Prospero, J. M., Blades, E., Mathison, G., and Naidu, R.: Interhemispheric transport of viable fungi and bacteria from Africa to the Caribbean with soil dust, *Aerobiologia*, 21, 1–19, 2005.
- Raynal, G.: Cinétique de la production d'ascospores de *Sclerotinia trifoliorum* Eriks en chambre de culture et en conditions climatiques naturelles. Incidences pratiques et épidémiologiques, *Agronomie*, 10, 561–572, 1990.
- Ribes, J. A., Vanover-Sams, C. L., and Baker, D. J.: Zygomycetes in human disease, *Clinical Microbiology Reviews*, 13, 236–301, 2000.
- Richardson, M. J.: The occurrence of airborne *Didymella* spores in Edinburgh, *Mycological Res.*, 100, 213–216, 1996.
- Rogers, L. A. and Meier, F. C.: The collection of micro-organisms above 36 000 feet/The Na-

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

tional Geographic Society – U.S. Army Air Corps Stratosphere Flight of 1935 in the Balloon “Explorer II”, National Geographic Society – Contributed Technical Papers – Stratospheric Series, 2, 146–151, 1936.

Rossi, V., Giosue, S., and Bugiani, R.: Influence of air temperature on the release of ascospores of *Venturia inaequalis*, J. Phytopathol., 151, 50–58, 2003.

Rossmann, A. Y.: Strategy for an all-taxa inventory of fungal biodiversity, in: Biodiversity and Terrestrial Ecosystems, edited by: Peng, C.-I. and Chou, C. H., Inst. Botany, Acad. Sinica Monograph Series, 14, 169–194, 1994.

Scheppergrell, W.: Airplane tests of hay fever pollen density in the upper air, Medical Journal and Record, 119, 185–189, 1924.

Schnell, R. G. and Vali, G.: Atmospheric ice nuclei from decomposing vegetation, Nature, 236, 163–165, 1972.

Seinfeld, J. H. and Pandis, S. N.: Atmospheric chemistry and physics: From air pollution to climate change, John Wiley, New York, 1998.

Simoneit, B. R. T. and Mazurek, M. A.: Organic-matter of the troposphere. 2. Natural background of biogenic lipid matter in aerosols over the rural western United-States, Atmos. Environ., 16, 2139–2159, 1982.

Stensvand, A., Amundsen, T., Semb, L., Gadoury, D. M., and Seem, R. C.: Discharge and dissemination of ascospores by *Venturia inaequalis* during dew, Plant Disease, 82, 761–764, 1998.

Sterling, M., Rogers, C., and Levetin, E.: An evaluation of two methods used for microscopic analysis of airborne fungal spore concentrations from the Burkard Spore Trap, Aerobiologia, 15, 9–18, 1999.

Sun, J. and Ariya, P. A.: Atmospheric organic and bio-aerosols as cloud condensation nuclei (CCN): A review, Atmos. Environ., 40, 795–820, 2006.

Suzuki, Y., Kawakami, M., and Akasaka, K.: H-1 NMR application for characterizing water-soluble organic compounds in urban atmospheric particles, Environ. Sci. Technol., 35, 2656–2664, 2001.

Tate, K. G. and Wood, P. N.: Potential ascospore production and resulting blossom blight by *Monilinia fructicola* in unsprayed peach trees, New Zealand Journal of Crop and Horticultural Science, 28, 219–224, 2000.

Taylor, P. E., Flagan, R. C., Miguel, A. G., Valenta, R., and Glovsky, M. M.: Birch pollen rupture and the release of aerosols of respirable allergens, Clinical and Experimental Allergy, 34,

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

- 1591–1596, 2004.
- Taylor, P. E. and Jonsson, H.: Thunderstorm asthma, *Current Allergy and Asthma Reports*, 4, 409–413, 2004.
- Trail, F., Gaffoor, I., and Vogel, S.: Ejection mechanics and trajectory of the ascospores of *Gibberella zeae* (anamorph *Fusarium graminearum*), *Fungal Genetics and Biology*, 42, 528–533, 2005.
- Trail, F., Xu, H. X., Loranger, R., and Gadoury, D.: Physiological and environmental aspects of ascospore discharge in *Gibberella zeae* (anamorph *Fusarium graminearum*), *Mycologia*, 94, 181–189, 2002.
- 10 Troutt, C. and Levetin, E.: Correlation of spring spore concentrations and meteorological conditions in Tulsa, Oklahoma, *Int. J. Biometeorol.*, 45, 64–74, 2001.
- Turner, J. C. R. and Webster, J.: Mass and momentum-transfer on the small-scale – how do mushrooms shed their spores, *Chem. Eng. Sci.*, 46, 1145–1149, 1991.
- Turner, J. C. R. and Webster, J.: Mushroom spores – The analysis of Buller's drop, *Chem. Eng. Sci.*, 50, 2359–2360, 1995.
- 15 Venette, J.: Sclerotinia spore formation, transport and infection, in: *Proceedings of the Sclerotinia Workshop*, 4–7, 1998.
- Wainwright, M., Wickramasinghe, N. C., Narlikar, J. V., and Rajaratnam, P.: Microorganisms cultured from stratospheric air samples obtained at 41 km, *FEMS Microbiol. Lett.*, 218, 161–165, 2003.
- 20 Warner, J. and Braun, P. G.: Discharge of *Venturia inaequalis* ascospores during daytime and nighttime wetting periods in Ontario and Nova Scotia, *Can. J. Plant Pathol.*, 14, 315–321, 1992.
- Watson, I. A. and DeSousa, C. N. A.: Long distance transport of spores of *Puccinia graminis tritici* in the southern hemisphere, *Proceedings of The Linnean Society of New South Wales*, 106, 311–321, 1983.
- 25 Webster, J., Davey, R. A., Smirnoff, N., Fricke, W., Hinde, P., Tomos, D., and Turner, J. C. R.: Mannitol and hexoses are components of Buller's drop, *Mycological Res.*, 99, 833–838, 1995.
- 30 Webster, J., Davey, R. A., and Turner, J. C. R.: Vapor as the source of water in Buller's drop, *Mycological Res.*, 93, 297–302, 1989.
- Wu, P. C., Tsai, J. C., Li, F. C., Lung, S. C., and Su, H. J.: Increased levels of ambient fungal spores in Taiwan are associated with dust events from China, *Atmos. Environ.*, 38, 4879–

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

4886, 2004.

Yeo, H.-G. and Kim, J.-H.: SPM and fungal spores in the ambient air of west Korea during the Asian dust (Yellow sand) period, Atmos. Environ., 36, 5437–5442, 2002.

Yttri, K. E., Dye, C., and Kiss, G.: Ambient aerosol concentrations of sugars and sugar-alcohols at four sites in Norway, Nordic Society for Aerosol Research (NOSA) Aerosol Symposium, Göteborg, Sweden, 2005.

Zhang, Q. and Anastasio, C.: Free and combined amino compounds in atmospheric fine particles ($PM_{2.5}$) and fog waters from Northern California, Atmos. Environ., 37, 2247–2258, 2003.

ACPD

6, 11317–11355, 2006

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Active discharge of spores by Ascomycota (AAM) and Basidiomycota (ABM).

Amount	Unit	Species	References
Ascomycota			
$2\text{--}37 \times 10^6$	per apothecium	<i>Monilinia fructicola</i>	(Hong and Michailides, 1998)
$3\text{--}24 \times 10^6$	per apothecium	<i>Cookeina sulcipes</i>	(Ingold, 1971)
$0.2\text{--}4.7 \times 10^6$	per apothecium	<i>Sclerotinia trifoliorum</i>	(Raynal, 1990)
$2\text{--}30 \times 10^6$	per apothecium	<i>Sclerotinia sclerotiorum</i>	(Venette, 1998)
$0.2\text{--}3 \times 10^{12}$	per ha	<i>Sclerotinia sclerotiorum</i>	(Venette, 1998)
Basidiomycota			
4×10^7	per fruiting body and hour	<i>Psalliota campestris</i>	(Buller, 1909)
1×10^8	per fruiting body and hour	<i>Coprinus comatus</i>	(Buller, 1909)
$1\text{--}10 \times 10^{10}$	per fruiting body and year	<i>Polyporus squamosus</i>	(Buller, 1909)
6.8×10^8	per fruiting body and week	<i>Daedalea confragosa</i>	(Buller, 1909)
3×10^{10}	per fruiting body and day	<i>Ganoderma applanatum</i>	(Meredith, 1973)

Table 2. Number concentrations of actively discharged ascospores, AAS (a), and actively discharged basidiospores, ABS (b), observed in ambient air.

AAS Concentration (10 ³ m ⁻³)	Species	Location and Time	References
(a)			
0–39	<i>Monilinia fructicola</i>	Hastings, NZ (August–September)	(Tate and Wood, 2000) ^a
0.1–9.3	<i>Gibberella zeae</i>	Quebec, Canada (July)	(Paulitz, 1996) ^b
0–15.2	<i>Gibberella zeae</i>	Manitoba, Canada (July–August)	(Inch et al., 2005)
0.01–1.5	<i>Gibberella zeae</i>	Ottawa, Canada (June–July)	(Fernando et al., 2000)
≤2.0	<i>Leptosphaeria</i>	Ontario, Canada (May–October)	(Li and Kendrick, 1995)
0.04–2.1	<i>Venturia inaequalis</i>	Ontario, Canada (April–May)	(Warner and Braun, 1992)
7.4	<i>Sclerotinia sclerotiorum</i>	USA	(Venette, 1998)
0.1–1	<i>Gibberella zeae</i>	Pennsylvania, USA (April–October)	Ayers et al., 1975, cited by Paulitz (1996)
≤2.5	various	Rochester, USA (April–September)	(Decco et al., 1998)
0.5–2.2	various	Oklahoma, USA (September)	(Sterling et al., 1999)
0.1–45	various	Oklahoma, USA (May)	(Troutt and Levetin, 2001)
0.1–15.6	<i>Venturia inaequalis</i>	Southeastern Norway (April–June)	(Stensvand et al., 1998)
≤0.6	various	Derby, UK (January–December)	(Newson et al., 2000)
≤2000	<i>Didymella exitialis</i>	Blandford, UK (August)	(Frankland and Gregory, 1973)
≤4.4	<i>Didymella exitialis</i>	Edinburgh, UK (July–October)	(Richardson, 1996)
0.03–5.9	<i>Venturia inaequalis</i>	Northern Italy (March–April)	(Rossi et al., 2003)
0–14.3	<i>Pleospora allii</i>	Cordoba, Spain (March–May)	(Prados-Ligerot et al., 2003)
≤90	<i>Phyllachora maydis</i>	Poza Rica, Mexico (February–April)	(Hock et al., 1995) ^b
2.5–3.3	various	Taiwan (September–April)	(Wu et al., 2004)
7.4	various	Balbina, Brazil (July)	this work
(b)			
≤2.8	various	Ontario, Canada (May–October)	(Li and Kendrick, 1995)
0–0.05	Rusts	Rochester, USA (April–September)	(Decco et al., 1998)
0–0.25	Smuts	Rochester, USA (April–September)	(Decco et al., 1998)
0–0.5	various	Rochester, USA (April–September)	(Decco et al., 1998)
0.1–5.5	various	Oklahoma, USA (May)	(Troutt and Levetin, 2001)
0.6–1.6	various	Oklahoma, USA (September)	(Sterling et al., 1999)
≤3	various	Oklahoma, USA (May–November)	(Levetin, 1990)
≤30	various	Harpندن, UK (July–September)	(Gregory and Hirst, 1952)
≤10	various	Cardiff, UK (June–October)	(Adams et al., 1968)
5.4	various	Derby, UK (January–December)	(Newson et al., 2000)
≤3	various	Bern, Switzerland (June–October)	(Helbling et al., 2002)
0.5–6	various	Saudi Arabia (January–December)	(Hasnain et al., 2005)
0–0.15	Rusts	Saudi Arabia (January–December)	(Hasnain et al., 2005)
0.5–4	Smuts	Saudi Arabia (January–December)	(Hasnain et al., 2005)
≤4.6	various	Mexico City, Mexico (January–November)	(Calderon et al., 1995)
1.3–2.9	various	Taiwan (April–September)	(Wu et al., 2004)
0.06	Rusts	Taiwan (September–April)	(Wu et al., 2004)
0.5	Smuts	Taiwan (September–April)	(Wu et al., 2004)
3.6	Rusts	Balbina, Brazil (July)	this work
9.2	Smuts	Balbina, Brazil (July)	this work

^a original data normalized by time; ^b data from infested plots.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 3. Mannitol mass concentrations in ambient air observed for different ranges of aerosol particle size (aerodynamic diameter), sampling locations, and seasons.

Average Concentration (ng m^{-3})	Concentration Range (ng m^{-3})	Particle Diameter (μm)	Location and Time	References
			Extratropical	
0.7	0.5–1.3	≤ 1	Hyytiälä, Finland (fall)	(Kourtchev et al., 2005a)
1.9	1.2–3.4	≤ 1	Hyytiälä, Finland (summer)	(Kourtchev et al., 2005a)
10.1	1.3–29	≤ 2.5	K-pusztá, Hungary (summer, day)	(Ion et al., 2005)
2.3	0.6–12	≤ 2.5	K-pusztá, Hungary (summer, night)	(Ion et al., 2005)
10.7	5.4–26	≤ 2.5	Jülich, Germany (summer)	(Kourtchev et al., 2005b)
–	3–66	≤ 7	Kobe City, Japan	(Suzuki et al., 2001)
–	1.6–23	≤ 10	Melpitz, Germany (spring)	(Carvalho et al., 2003)
–	0.5–88	≤ 10	Hyytiälä, Finland (summer)	(Carvalho et al., 2003)
4.3	0–10	≤ 10	Birkenes, Norway	(Yttri et al., 2005)
8.1	1.1–19	≤ 10	Oslo, Norway	(Yttri et al., 2005)
20.0	9–30	≤ 10	Oslo, Norway	(Yttri et al., 2005)
26.0	7.8–70	≤ 10	Ghent, Belgium (winter)	(Pashynska et al., 2002)
97.0	31–220	≤ 10	Ghent, Belgium (summer)	(Pashynska et al., 2002)
4.2	0.9–14	0.06–16	Elverum, Norway (winter)	(Yttri et al., 2005)
18.0	12–24	0.06–16	Elverum, Norway (summer)	(Yttri et al., 2005)
			Tropical (Brazil), Wet Season	
22.3	4.7–56	≤ 2.5	Reserva Biológica Jarú, Rondônia (1999)	(Graham et al., 2002)
26.3	9.9–50	≤ 2.5	FNS, Rondônia (1999)	(Graham et al., 2002)
20.8	11–31	≤ 2.5	FNS, Rondônia (2002)	(Decesari et al., 2006)
9.4	–	≤ 2.5	Balbina, Amazonas (day) (2001)	(Claeys et al., 2004)
8.4	–	≤ 2.5	Balbina, Amazonas (night) (2001)	(Claeys et al., 2004)
15.2 ^a	9.6–24	≤ 2.5	Balbina, Amazonas (day) (2001)	(Graham et al., 2003b)
13.0	–	≤ 2.5	Balbina, Amazonas (day) (2001)	(Graham et al., 2003b)
17.0	–	≤ 2.5	Balbina, Amazonas (night) (2001)	(Graham et al., 2003b)
112.0	58–330	TSP ^b	Balbina, Amazonas (1998)	(Claeys et al., 2004)
32.0	–	≥ 2.5	Balbina, Amazonas (day) (2001)	(Claeys et al., 2004)
68.0	–	≥ 2.5	Balbina, Amazonas (night) (2001)	(Claeys et al., 2004)
53.3 ^a	24–102	≥ 2.5	Balbina, Amazonas (day) (2001)	(Graham et al., 2003b)
29.0	–	≥ 2.5	Balbina, Amazonas (day) (2001)	(Graham et al., 2003b)
78.0	–	≥ 2.5	Balbina, Amazonas (night) (2001)	(Graham et al., 2003b)

(^a) average of campaign (19–28 July 2001); (^b) TSP: total suspended particles.

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 4. Hexose (glucose, Glc; fructose, Fru) mass concentrations in ambient air observed for different ranges of aerosol particle size (aerodynamic diameter), sampling locations, and seasons.

Substance	Average Concentration (ng m ⁻³)	Concentration Range (ng m ⁻³)	Particle Diameter (μm)	Location and Time	References
Glc	15	11–26	≤2.5	Extratropical	
Glc	–	1.3–41	≤10	Jülich, Germany (summer)	(Kourtchev et al., 2005b)
Glc	3.7	0.9–7.2	≤10	Hyttälä, Finland (summer)	(Carvalho et al., 2003)
Glc	47	8.4–93	≤10	Birkenes, Norway	(Yttri et al., 2005)
Glc	22	5.4–32	≤10	Oslo, Norway	(Yttri et al., 2005)
Glc	19	10–34	≤10	Elverum, Norway (winter)	(Yttri et al., 2005)
Glc	–	28–180	≤10	Elverum, Norway (summer)	(Yttri et al., 2005)
Glc	73	30–153	≤10	Melpitz, Germany (spring)	(Carvalho et al., 2003)
Glc	270	110–610	≤10	Ghent, Belgium (winter)	(Pashynska et al., 2002)
Fru	10	6–20	≤10	Ghent, Belgium (summer)	(Pashynska et al., 2002)
Fru	1.4	0.3–3.9	≤2.5	Jülich, Germany (summer)	(Kourtchev et al., 2005b)
Fru	42	4.6–90	≤10	Birkenes, Norway	(Yttri et al., 2005)
Fru	11	3.4–21	≤10	Oslo, Norway	(Yttri et al., 2005)
Fru	11	3.3–25	≤10	Elverum, Norway (winter)	(Yttri et al., 2005)
Fru	37	10–126	≤10	Elverum, Norway (summer)	(Yttri et al., 2005)
Fru	193	39–440	≤10	Ghent, Belgium (winter)	(Pashynska et al., 2002)
				Ghent, Belgium (summer)	(Pashynska et al., 2002)
				Tropical (Brazil), Wet Season	
Glc & Fru	32.4	6.9–64	≤2.5	Reserva Biológica Jarú, Rondônia (1999)	(Graham et al., 2002)
Glc and Fru	48.6	17–82	≤2.5	FNS, Rondônia (1999)	(Graham et al., 2002)
Fru	4.0	2.5–5.9	≤2.5	FNS, Rondônia (2002)	(Decesari et al., 2006)
Glc	15.6	–	≤2.5	Balbina, Amazonas (day) (2001)	(Claeys et al., 2004)
Glc	0.6	–	≤2.5	Balbina, Amazonas (night) (2001)	(Claeys et al., 2004)
Glc and Fru	12.6	3.6–26	≤2.5	Balbina, Amazonas (avg) (2001)	(Graham et al., 2003b)
Glc and Fru	20	–	≤2.5	Balbina, Amazonas (day) (2001)	(Graham et al., 2003b)
Glc and Fru	5.9	–	≤2.5	Balbina, Amazonas (night) (2001)	(Graham et al., 2003b)
Glc	29	12–76	TSP	Balbina, Amazonas (1998)	(Claeys et al., 2004)
Glc	134	–	≥2.5	Balbina, Amazonas (day) (2001)	(Claeys et al., 2004)
Glc	2.7	–	≥2.5	Balbina, Amazonas (night) (2001)	(Claeys et al., 2004)
Glc and Fru	76.7	3.6–200	≥2.5	Balbina, Amazonas (avg) (2001)	(Graham et al., 2003b)
Glc and Fru	146	–	≥2.5	Balbina, Amazonas (day) (2001)	(Graham et al., 2003b)
Glc and Fru	7.2	–	≥2.5	Balbina, Amazonas (night) (2001)	(Graham et al., 2003b)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 5. Potassium mass concentrations in ambient air observed for different ranges of aerosol particle size (aerodynamic diameter) during the wet season in Brazil.

Average Concentration (ng m^{-3})	Particle Diameter (μm)	Location and Time	References
24.0	0.05–1.2	FNS, Rondônia (day)	(Fuzzi et al., 2006b)
68.0	0.05–1.2	FNS, Rondônia (night)	(Fuzzi et al., 2006b)
33.5	≤ 2	FNS, Rondônia	(Artaxo et al., 2002)
26.2	≤ 2	Reserva Biologica Jarú, Rondônia	(Artaxo et al., 2002)
27.1	≤ 2	Reserva Biologica Jarú, Rondônia	(Guyon et al., 2003)
32.1	≤ 2	Ducke Forest Reserve, Amazonas (Meteorological Site)	(Artaxo et al., 1990)
26.3	≤ 2	Ducke Forest Reserve, Amazonas (Tower Site)	(Artaxo et al., 1990)
24.2	≤ 2	ZF1 site, Amazonas	(Artaxo et al., 1990)
18.0	≤ 2	Balbina, Amazonas	(Formenti et al., 2001)
29.2	≤ 2	Balbina, Amazonas	(Graham et al., 2003a)
94.0	≤ 2	Alta Floresta, Mato Grosso	(Echalar et al., 1998)
220.0	≤ 2	Alta Floresta, Mato Grosso	(Maenhaut et al., 2002)
14.0	1.2–10	FNS, Rondônia (day)	(Fuzzi et al., 2006b)
49.0	1.2–10	FNS, Rondônia (night)	(Fuzzi et al., 2006b)
76.7	2–10	FNS, Rondônia	(Artaxo et al., 2002)
73.7	2–10	Reserva Biologica Jarú, Rondônia	(Artaxo et al., 2002)
107.6	2–10	Reserva Biologica Jarú, Rondônia	(Guyon et al., 2003)
112.1	2–15	Ducke Forest Reserve, Amazonas (Meteorological Site)	(Artaxo et al., 1990)
94.6	2–15	Ducke Forest Reserve, Amazonas (Tower Site)	(Artaxo et al., 1990)
87.3	2–15	ZF1 site, Amazonas	(Artaxo et al., 1990)
69.0	2–10	Balbina, Amazonas	(Formenti et al., 2001)
52.6	2–10	Balbina, Amazonas	(Graham et al., 2003a)
270.0	2–10	Alta Floresta, Mato Grosso	(Echalar et al., 1998)
240.0	2–10	Alta Floresta, Mato Grosso	(Maenhaut et al., 2002)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Table 6. Chloride mass concentrations in ambient air observed for different ranges of aerosol particle size (aerodynamic diameter) during the wet season in Amazonia.

Average Concentration (ng m ⁻³)	Particle Diameter (μm)	Location and Time	References
5.5	≤2	FNS, Rondônia	(Artaxo et al., 2002)
5.1	≤2	Reserva Biologica Jarú, Rondônia	(Artaxo et al., 2002)
9.5	≤2	Ducke Forest Reserve, Amazonas (Meteorological Site)	(Artaxo et al., 1990)
13.0	≤2	Ducke Forest Reserve, Amazonas (Tower Site)	(Artaxo et al., 1990)
8.9	≤2	ZF1 site, Amazonas	(Artaxo et al., 1990)
65.0	≤2	Balbina, Amazonas	(Formenti et al., 2001)
4.8	≤2	Balbina, Amazonas	(Graham et al., 2003a)
2.3	≤2	Alta Floresta, Mato Grosso	(Echalar et al., 1998)
37.0	≤2	Alta Floresta, Mato Grosso	(Maenhaut et al., 2002)
14.3	2–10	FNS, Rondônia	(Artaxo et al., 2002)
9.4	2–10	Reserva Biologica Jarú, Rondônia	(Artaxo et al., 2002)
7.8	2–10	Reserva Biologica Jarú, Rondônia	(Guyon et al., 2003)
55.0	2–15	Ducke Forest Reserve, Amazonas (Meteorological Site)	(Artaxo et al., 1990)
33.2	2–15	Ducke Forest Reserve, Amazonas (Tower Site)	(Artaxo et al., 1990)
52.5	2–15	ZF1 site, Amazonas	(Artaxo et al., 1990)
155.0	2–10	Balbina, Amazonas	(Formenti et al., 2001)
59.1	2–10	Balbina, Amazonas	(Graham et al., 2003a)
41.0	2–10	Alta Floresta, Mato Grosso	(Echalar et al., 1998)
65.0	2–10	Alta Floresta, Mato Grosso	(Maenhaut et al., 2002)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Table 7. Total particulate matter mass concentrations in ambient air observed for particles with aerodynamic diameters of 1–2 μm to 10–15 μm during the wet season in Amazonia.

Mass Concentration ($\mu\text{g m}^{-3}$)	Particle Diameter (μm)	Location and Time	References
1.0	1.2–10	FNS, Rondônia, (DLPI, day)	(Fuzzi et al., 2006b)
4.3	1.2–10	FNS, Rondônia (DLPI, night)	(Fuzzi et al., 2006b)
1.8	1.2–10	FNS, Rondônia (MOUDI, day)	(Fuzzi et al., 2006b)
6.9	1.2–10	FNS, Rondônia (MOUDI, night)	(Fuzzi et al., 2006b)
5.7	2–10	FNS, Rondônia	(Artaxo et al., 2002)
5.1	2–10	Reserva Biologica Jarú, Rondônia	(Artaxo et al., 2002)
6.6	2–10	Reserva Biologica Jarú, Rondônia	(Guyon et al., 2003)
8.0	2–15	Ducke Forest Reserve, Amazonas (Meteorological Site)	(Artaxo et al., 1990)
7.6	2–15	Ducke Forest Reserve, Amazonas (Tower Site)	(Artaxo et al., 1990)
6.5	2–15	ZF1 site, Amazonas	(Artaxo et al., 1990)
5.8	2–10	Balbina, Amazonas	(Formenti et al., 2001)
2.8	2–10	Balbina, Amazonas (day)	(Graham et al., 2003a)
5.5	2–10	Balbina, Amazonas (night)	(Graham et al., 2003a)
16.4	2–10	Alta Floresta, Mato Grosso	(Echalar et al., 1998)
15.1	2–10	Alta Floresta, Mato Grosso	(Maenhaut et al., 2002)

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

**Contribution of fungi
to biogenic aerosols**

W. Elbert et al.

Table 8. Liquid concentrations of species ejected with AAS (Trail et al., 2005) and ABS (Webster et al., 1995) taken as representative average values for budget calculations.

Species	Buller's Drop (pg/Spore)	Ascus Sap (pg/Ascus)
Mannitol	5.3	4.7
Hexoses	3.8	nd
Potassium	nd	45.9
Chloride	nd	14.3
Solutes	9.1	64.9

nd: not determined

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

Table 9. Measured and calculated concentrations of spores and related chemical components in air particulate matter from Balbina: measured number concentrations of ABS and AAS; calculated mass concentrations of solutes and spores (calculations as detailed in Sect. 4).

	ABS		AAS		AAS + ABS		
	Day	Night	Day	Night	Day	Night	Average
Spores (m^{-3})	1800	12 772	2964	7416	4764	20 188	12 476
Mannitol (ng m^{-3})	9.5	67.7	1.7	4.3	11.2	72	41.6
Hexoses (ng m^{-3})	6.8	48.5	nd	nd	6.8	48.5	27.7
Potassium (ng m^{-3})	nd	nd	17.3	43.3	17.3	43.4	29.8
Chloride (ng m^{-3})	nd	nd	5.3	13.3	5.3	13.3	9.3
Solute Mass (ng m^{-3})	16.4	116	24.3	60.9	40.7	177	108
Spore Mass (ng m^{-3})	118	835	592	1483	710	2318	1514

nd: not determined

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

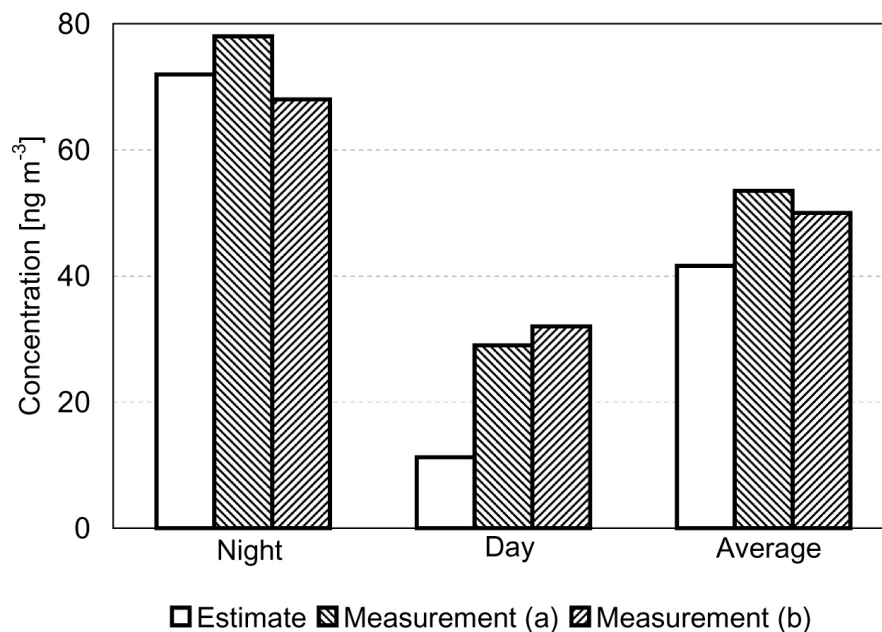


Fig. 1. Mannitol concentrations in ambient air in Amazonia (Balbina, Brazil): estimate from spore counts (this study) compared to measurements of (a) Graham et al. (2003b; plotted: mean values of 6 samples; night-time standard deviation (SD): $\pm 15 \text{ ng m}^{-3}$; day-time SD: $\pm 8 \text{ ng m}^{-3}$; range of diurnal average: $24\text{--}102 \text{ ng m}^{-3}$) and (b) Claeys et al. (2004; plotted: mean values).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

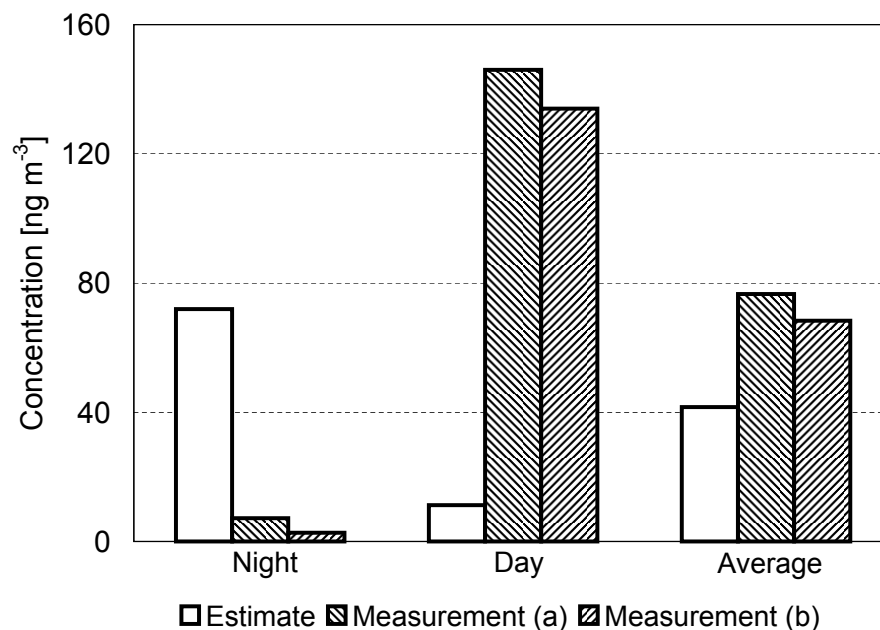


Fig. 2. Hexose (glucose and fructose) concentrations in ambient air in Amazonia (Balbina, Brazil): estimate from spore counts (this study) compared to measurements of (a) Graham et al. (2003b; plotted: mean values of 6 samples; night-time SD: $\pm 5 \text{ ng m}^{-3}$; day-time SD: $\pm 45 \text{ ng m}^{-3}$; range of diurnal average: $4\text{--}200 \text{ ng m}^{-3}$) and (b) Claeys et al. (2004; plotted: mean values).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

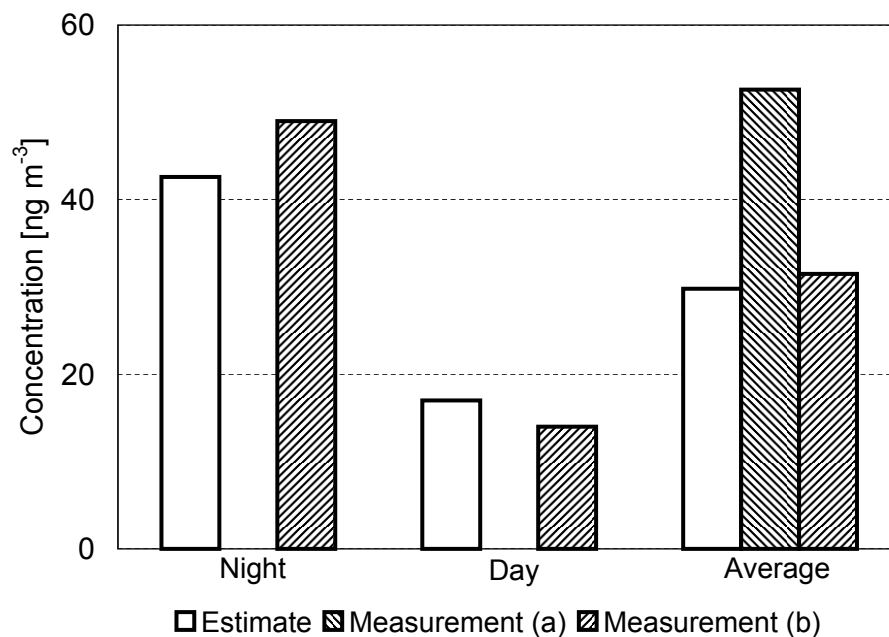


Fig. 3. Potassium concentrations in ambient air in Amazonia: estimate from spore counts at Balbina (this study) compared to measurements at (a) Balbina (Graham et al., 2003a; plotted: mean value of 8 samples; SD of diurnal average: $\pm 29 \text{ ng m}^{-3}$) and (b) FNS, Rondônia (Fuzzi et al., 2006b; plotted: mean values; night-time SD: $\pm 36 \text{ ng m}^{-3}$; day-time SD: $\pm 10 \text{ ng m}^{-3}$).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Contribution of fungi to biogenic aerosols

W. Elbert et al.

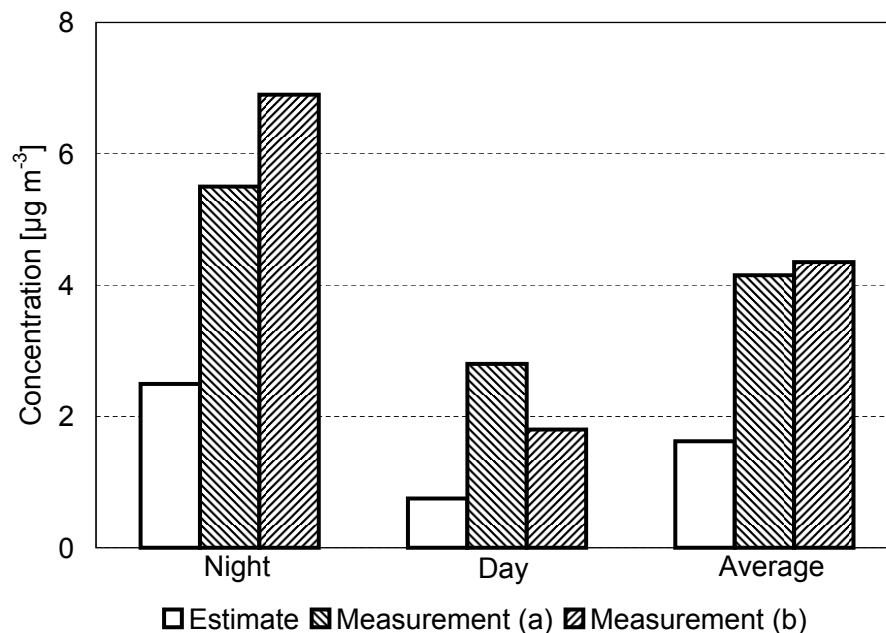


Fig. 4. Aerosol mass concentration in ambient air in Amazonia: estimate from spore counts at Balbina (this study) compared to measurements at (a) Balbina (Graham et al., 2003a; plotted: mean values) and (b) FNS, Rondônia (Fuzzi et al., 2006b; plotted: mean values; night-time SD: $\pm 5.2 \mu\text{g m}^{-3}$; day-time SD: $\pm 1.3 \mu\text{g m}^{-3}$).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU